Discipline Course-I

Semester-II

Paper No: Electricity and Magnetism

Lesson: Magnetic Properties of Matter

Lesson 4.1: Magnetic parameters in matter, magnetization, magnetic field, susceptibility, permeability, relation between B, H, M

Lesson Developer: Dr. Chetana Jain

College/ Department: Hans Raj College, University of Delhi

Table of Contents

Chapter: Magnetic Properties of Matter

Learning Objective

This lesson aims at the following student learning objectives.

- Effect of magnetic field on the motion of electrons in material medium
    - Motion of electron around the nucleus
    - Motion of electron about its own axis of rotation
- Understanding the concept of magnetization
- Concept of free and bound current
- Importance of magnetic parameters like susceptibility and permeability
- Characteristic features of various types of magnetic materials
    - Diamagnetic material
    - Paramagnetic material

Introduction

On microscopic scale, all magnetic materials comprise of tiny current loops where electrons are in motion. This motion can either be in the form of spinning of electrons about their axis or revolution of electrons in their orbits around the positively charged nucleus. It can also be due to the spin of nucleus about its axis, but its effect is extremely small and negligible.

On macroscopic scale, these current loops can be considered as magnetic dipoles. Atoms in any material are held in random orientations, therefore, these magnetic dipoles get cancelled and the material is suitably regarded as non-magnetic.

When an external magnetic field is applied to the material, then a force is exerted on the electrons. Depending on the atomic and molecular structure and the magnitude of the applied magnetic field, different materials respond differently and get magnetized to different degree. The microscopic magnetic dipoles are forced to align in a given direction, which can be either parallel or anti-parallel to the applied field.

In this lesson, we will first study the cause and effects of magnetization. Then we will discuss magnetization in linear materials which can be either diamagnetic or paramagnetic. Ferromagnetic materials, along with ferrimagnetism and anti-ferromagnetic materials will be covered in the next lesson.

Magnetization

Whenever an external magnetic field is applied to a material, it gets magnetically polarized or magnetized. This phenomenon is referred to as **magnetization**. Since all the materials are composed of atoms, the effect of magnetic field is primarily manifested in two major ways. The applied magnetic field primarily effects,

1. Orbital motion of electrons around the positively charged nucleus. (Motion 1 in *Figure 1*)

2. Spin motion of the electrons about their own axis of rotation. (Motion 2 in *Figure 1*) The arrow near the electron imply direction of its spin motion.

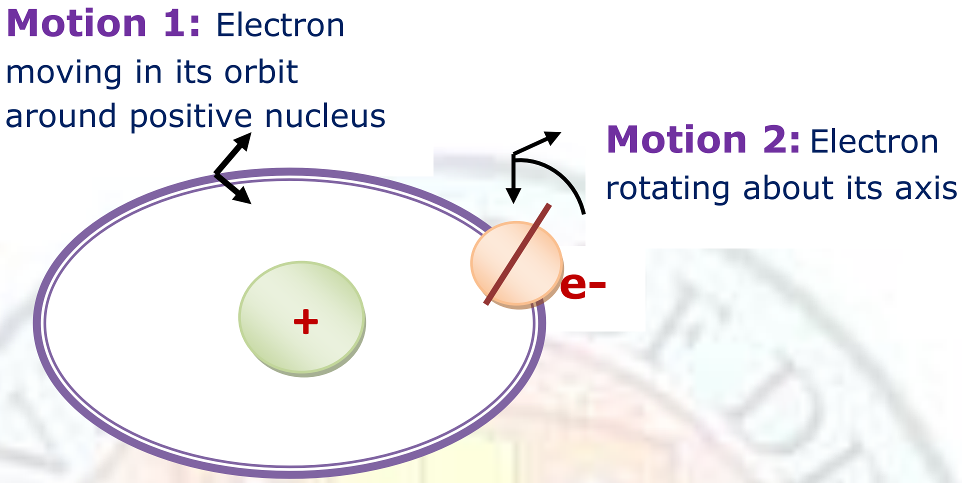


Figure 1

Effect of external magnetic field on the orbital motion of electron

We all know the famous Pauli's exclusion principle, according to which, no two electrons in an atom can have same set of quantum numbers. If electrons are present in the same energy shell, they must have opposite spin. Hence, all the atoms which have even number of electrons do not possess a net spin dipole moment, since their spins get cancelled out in pairs.

In addition to rotation about their axis, electrons are revolving around the positively charged nucleus and hence have an orbital dipole moment associated with them. Therefore, when external magnetic field is applied, the speed of electron in their orbits gets changed, such that the dipole moments get aligned in a direction opposite to the direction of applied magnetic field. The following derivation gives a detailed expression for the change in velocity of orbiting electron.

Assume that electrons (charge –e, mass m_e) revolve around the nucleus (charge +e) with a velocity v, in circular orbit (axis along x-direction) of radius r. See figure 2.

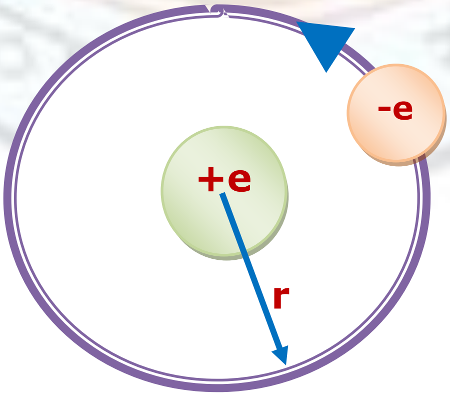


Figure 2

The coulomb force of attraction between positively charged nucleus and negatively charged electron = $- e^2/ (4\pi\varepsilon_0 r^2)$

The centripetal force on the electron $= m_e v^2/r$

∴ Initially the equation of motion is, Coulomb force = centripetal force.

The atom can be regarded as consisting of tiny current loops, with current I flowing through it, such that,

I = charge of particle/time period of revolution

$= - e\, v/2\, \pi\, r$

The corresponding orbital magnetic moment will be,

m = current x area of current loop

⇨ $m = (- e\, v/2\, \pi\, r) \times (\pi\, r^2)$

⇨ **m** $= - (e\, v\, r/2)$ (1)

Here, negative sign occurs due to negative charge of electron.

Now, a magnetic field **B** is applied in the positive x-direction and perpendicular to the plane of the circular orbit (see *Figure 3*). The arrows in the figure show the clockwise or anti-clockwise sense of rotation of the electron. This exerts a Lorentz force (Bev) on revolving electron, thereby changing its velocity.

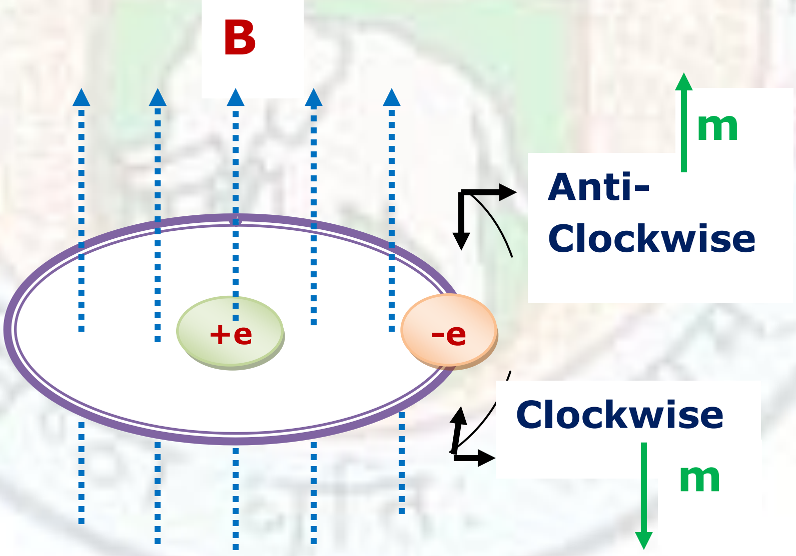


Figure 3

Hence equation of motion becomes,

Coulomb force + Lorentz force = centripetal force

$-e^2/ (4\pi\varepsilon_0 r^2) + (B\, (-e)\, v') = m_e v'^2/r$ (2)

Hence, change in velocity (from equations 1 and 2) will be,

$\Delta v = v' - v = (e\, r\, B)/\, (2m_e)$

Hence, from equation 1, the change in magnetic moment of the atom when a magnetic field is applied will be,

$$\boxed{\Delta \mathbf{m} = -\,(e\,\Delta v\; r/2)\;\; = -\,(e^2\, r^2\, \mathbf{B}/4m_e)} \quad \text{.................. } 2$$

The negative sign implies that **change in magnetic moment of the material is in opposite direction to that of the applied magnetic field**.

Conclusion: Looking at the above equations 1 and 2,

Case I (figure 4): If the electron is orbiting clockwise (as in figure 3), then its magnetic moment will be downward. It implies,

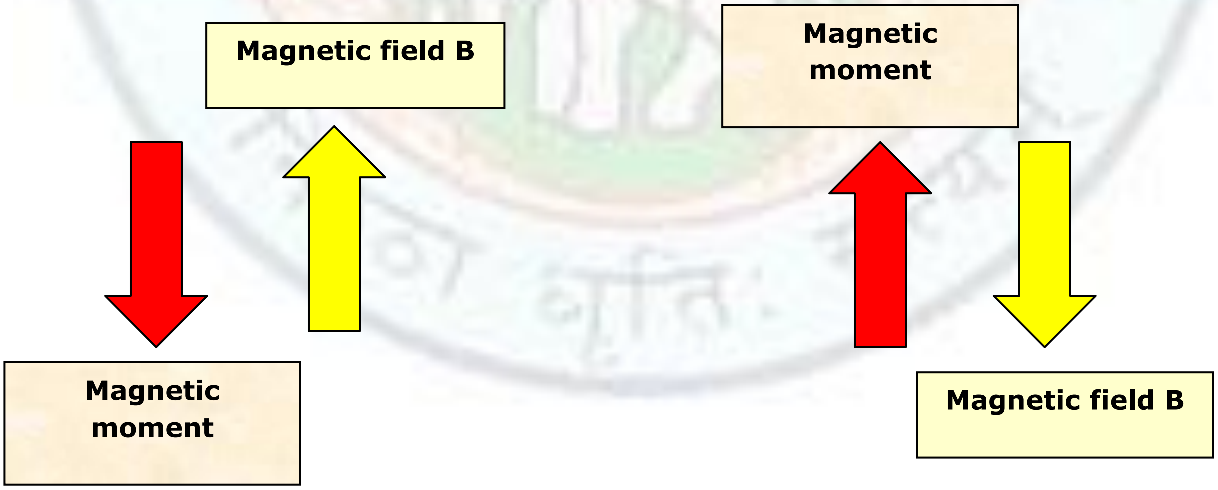
a. direction of magnetic moment is opposite to direction of **B**

b. Δ**v** is positive and velocity of electron increases

Case II (figure 4): If the electron is orbiting anti- clockwise (as in figure 3), then its magnetic moment will be upward. It implies,

a. direction of magnetic moment is parallel to direction of **B**

b. Δ**v** is negative and velocity of electron decreases.



(Case I) **(Case II)**

Figure 4

Effect of external magnetic field on the spin motion of electron

As mentioned before, motion of electrons about their own axis can be regarded as a current loop, with current I flowing through it. Atoms having unpaired and odd number of electrons have a net spin dipole moment associated with them. When external magnetic field is applied, a torque acts on these dipoles, thereby forcing them to line up in direction parallel to the direction of magnetic field.

As shown in the figure 5 below, consider a dipole (of length l and width w) oriented along an arbitrary direction, making angle θ with the y-axis.

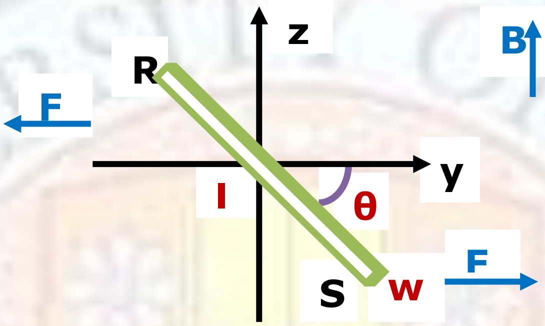


Figure 5

A magnetic field **B** is applied along the z-axis. Due to this, a force (**F**) is exerted on the dipole. Magnetic charge at point R is pulled towards left and magnetic charge at S is pulled towards right. The magnitude of force will be,

$F = I\,w\,B$

The net torque exerted on the dipole is given by,

$\zeta = l \times F = l\,F \sin\theta\,\mathbf{z} = I\,lw\,B \sin\theta\,\mathbf{z} = m\,B \sin\theta\,\mathbf{z}$

⇨ $\boldsymbol{\zeta} = \mathbf{m} \times \mathbf{B}$ (where m is the spin magnetic moment)

This torque will try to align the magnetic moments of the atom in a direction parallel to the direction of external applied magnetic field. See figure 6.

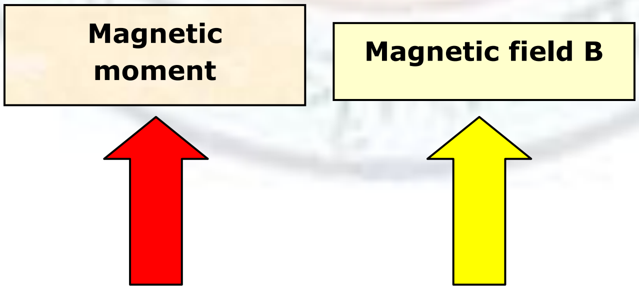


Figure 6

Techniques to magnetize a material

1. Place the specimen inside a coil and pass direct current through the coil for a short time.

2. Apply magnetic field to the molten form of the specimen and they allow it to solidify after removing the field.

Techniques to de-magnetize a material

1. Place the magnet inside a coil and pass alternating current through the coil for some time. With every opposite cycle of the current, the magnetization produced inside the magnet will reverse its direction. If we slowly remove the magnet out of the coil during each reversal of the current direction, then magnetization will simultaneously get reduced.

2. Heat the magnet to a temperature above its Curie temperature. This will increase the entropy of the constituent magnetic dipoles, which will thereby, get arranged in a statistical random manner. See figure 7.

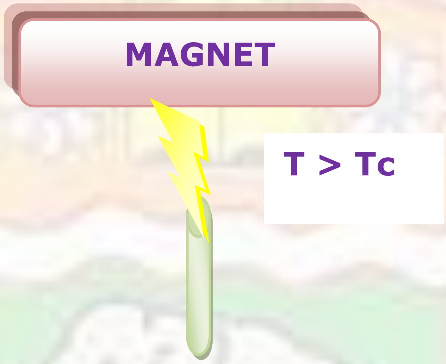


Figure 7

3. Put force or hammer the magnet repeatedly. This will de-range the internal ordering in the magnetic dipoles. The material therefore loses its magnetism. See figure 8.

(image of hammer taken from http://commons.wikimedia.org/wiki/File:Hammer_tapissier.jpg)

Figure 8

Magnetization vector M

Consider a non-magnetic material surface having a volume v. It consists of several dipoles, each having a dipole moment **m**. When an external magnetic field is applied, then the vector potential at a finite distance r away from each dipole will be given by,

$$\mathbf{A}\ (\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{\mathbf{m}\ x\ \mathbf{r}}{r^2}$$

Here, μ_0 is magnetic permeability of free space.

We know that magnetization vector **M** is total magnetic dipole moment per unit volume, therefore, if we consider an infinitesimally small volume element is $d\tau$, then,

$$\mathbf{m} = \mathbf{M}\ d\tau$$

Hence, total vector potential at a finite distance r from the surface will be equal to the magnetic vector potential due to all the dipoles.

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int \frac{M(r')\ x\ r}{r^2}\ d\tau'$$

$$= \frac{\mu_0}{4\pi}\int \left[\mathbf{M}(\boldsymbol{r}')\ x\ \left(\boldsymbol{\nabla}'\frac{1}{r}\right)\right] d\tau'$$

$$= \frac{\mu_0}{4\pi}\left[\int \frac{1}{r}\left\{\boldsymbol{\nabla}'\ x\ \mathbf{M}(\boldsymbol{r}')\right\} d\tau' - \int \boldsymbol{\nabla}'\ x\ \left\{\frac{\mathbf{M}(r')}{r}\right\}\ d\tau'\right]$$

$$= \frac{\mu_0}{4\pi}\left[\int \frac{1}{r}\left\{\boldsymbol{\nabla}'\ x\ \mathbf{M}(\boldsymbol{r}')\right\} d\tau'\right] + \frac{\mu_0}{4\pi}\left[\oint \frac{1}{r}\left\{\mathbf{M}(\boldsymbol{r}')\ x\ \boldsymbol{da}'\right\}\right]$$

$$= \frac{\mu_0}{4\pi}\left[\int_v \frac{\boldsymbol{J_b}(r')}{r}\ d\tau'\right] + \frac{\mu_0}{4\pi}\left[\oint_s \frac{\boldsymbol{K_b}(r')}{r}\ da'\right]$$

The above equation implies that due to the magnetization of a material, bound currents are produced, which exist within the material (volume current density $\mathbf{J_b} = \nabla\ x\ \mathbf{M}$) as well as on its surface (surface current density $\mathbf{K_b} = \mathbf{M}\ \mathbf{x}\ \mathbf{n}$). These bound currents are associated with the internal magnetic moments of the atom and cannot be controlled by an external source of electric field.

Hence (Figure 9) the total current density (**J**) through the material becomes equal to the bound current density ($\mathbf{J_{bound}}$) plus current density ($\mathbf{J_{free}}$) due to free electrons flowing due to an applied electric field.

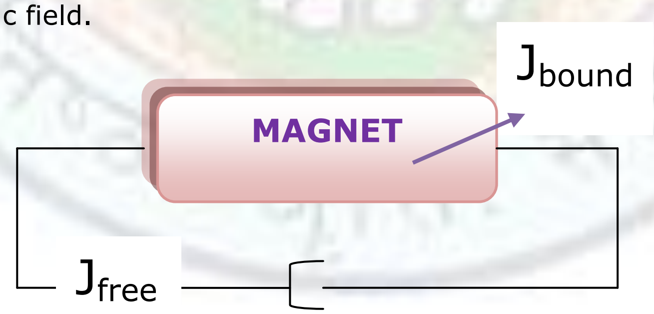


Figure 9

$$\mathbf{J} = \mathbf{J_{free}} + \mathbf{J_{bound}}$$

Therefore, from Ampere's circuital law,

$\frac{1}{\mu_o}(\nabla \, x \, \boldsymbol{B})$ = Total current per unit volume flowing through the Amperian loop

$= \mathbf{J_{free}} + \mathbf{J_{bound}}$

$= \mathbf{J_{free}} + (\nabla \, x \, \mathbf{M})$

⇨ $\mathbf{J_{free}} = \nabla \, x \left(\frac{1}{\mu_o}\boldsymbol{B} - \boldsymbol{M}\right)$

⇨ $\mathbf{J_{free}} = \nabla \, x \, \mathbf{H}$

⇨ $\oint \boldsymbol{H} \, . \, \boldsymbol{dl} = \boldsymbol{I_{free}}$

Where I_{free} is the total free current

Did You Know?

1. $\boldsymbol{\nabla . B}$ is always zero and **B** = μ_o $(\boldsymbol{H} + \boldsymbol{M})$. Therefore, even if, $\nabla.\mathbf{B} = 0$, we have, $\nabla.\boldsymbol{H} = -\nabla.\boldsymbol{M}$ which may or may not be zero.

2. Magnetic polarization ($\mathbf{P_m}$) and electric polarization ($\mathbf{P_e}$) are analogous properties. But while on one hand, $\mathbf{P_e}$ is mostly parallel to the direction of applied electric field **E**, $\mathbf{P_m}$ can be parallel or anti-parallel to **B**.

Diamagnetism

This type of magnetism normally occurs in all types of materials and is a universal phenomenon. In diamagnetic materials, the atoms/molecules do not possess any net spin magnetic moment. Therefore, diamagnetism is primarily due to orbital motion of electrons. It is a weak magnetism with a small magnitude and it therefore normally exists in atoms/molecules with even number of electrons, where other types of magnetisms (paramagnetism and ferromagnetisms) are absent. These materials are less sensitive to the external magnetic fields and hence they have a negative susceptibility.

Effect of external magnetic field

1. These materials are repelled by the external magnetic field and the magnetic dipoles get aligned in a direction opposite (anti-parallel) to that of magnetic field, as shown in figure 10.

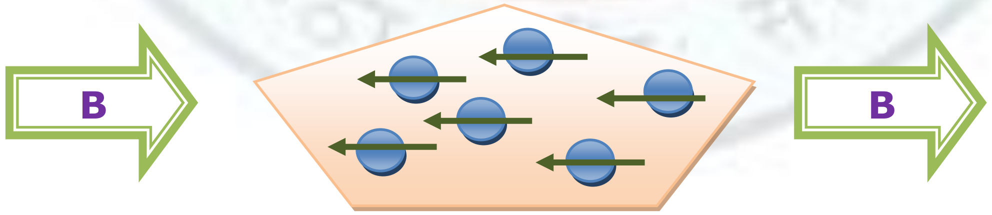


Figure 10

2. If the external applied magnetic field is uniform, then the material orients itself at right angles to the field, as shown in figure 11.

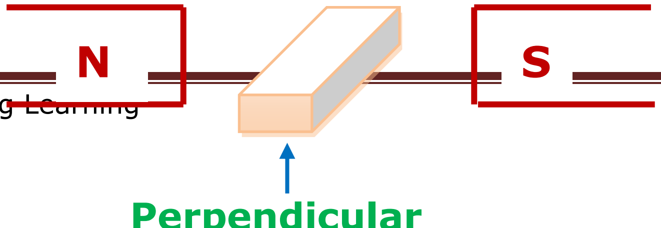


Figure 11

3. If the external magnetic field is non-uniform, then material moves from regions of higher magnetic field to those with lower magnetic field. In figure 12, the yellow arrow implies magnetic lines of force start from North Pole of a magnet and end at the South Pole. The original level of a diamagnetic material goes downwards when magnetic field is applied (as shown by orange arrow).

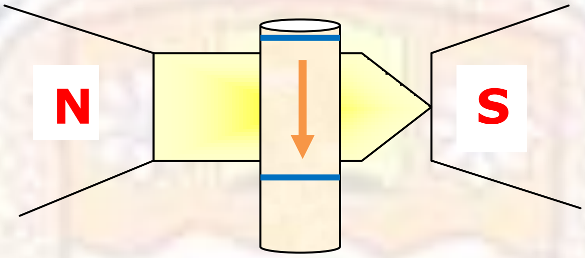


Figure 12

4. When the external magnetic field is removed, then all the magnetism is lost and dipoles once again become random in orientation, as shown in figure 13.

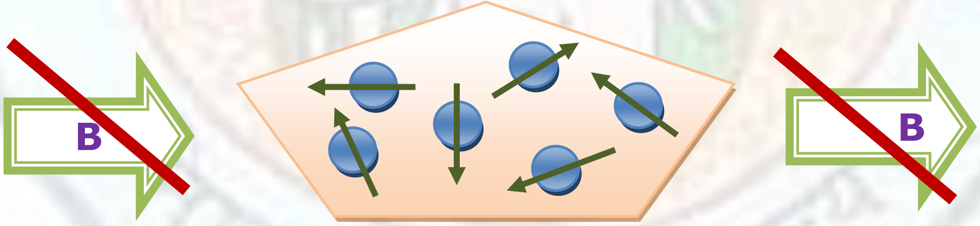


Figure 13

Important characteristics

1. They are Type 1 superconductors, which act as perfect diamagnetic material and do not allow magnetic lines of force to pass through them. See figure 14.

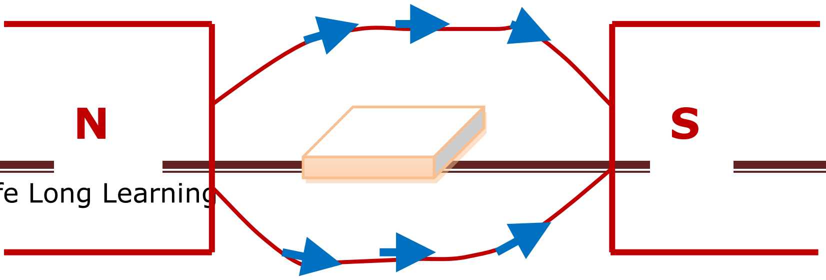


Figure 14

2. Permeability of diamagnetic material ($\mu_{diamagnetic}$) is less than that of free space (μ_o). The relative permeability is less than 1 and lines of force do not pass through the material. The variation of magnetic flux density **B** w.r.t applied magnetic field **H** is given in figure 15. The slope of the graph gives permeability of the material.

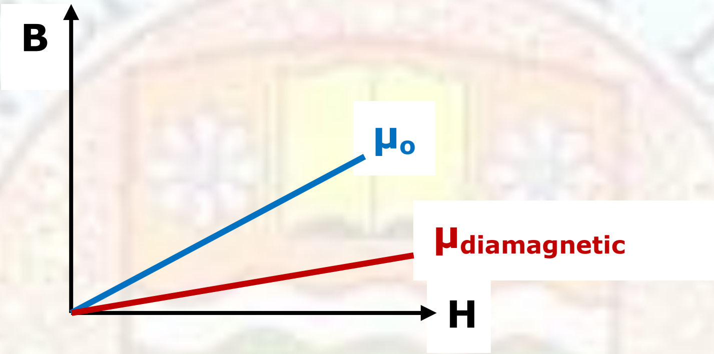


Figure 15

3. The diamagnetic materials cannot be magnetized easily and are very less sensitive to the applied magnetic field. They have negative susceptibility (χ), which is independent of temperature. The variation of magnetization vector **M** w.r.t. applied magnetic field **H** is shown in figure 16(a). The slope of the graph gives susceptibility. The temperature dependence of susceptibility is shown in figure 16(b).

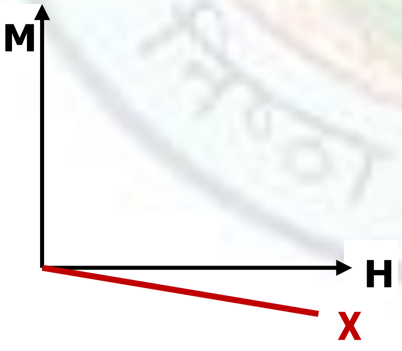


Figure 16(a)

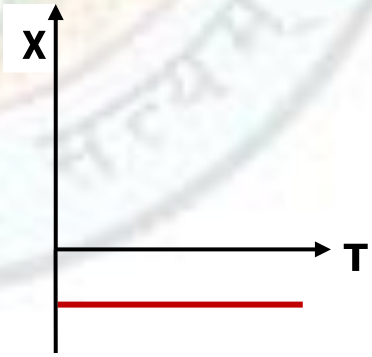


Figure 16(b)

4. Example: copper, gold, silver

Did You Know?

One of the important applications of a diamagnetic material is **magnetic levitation**. It is a technique to levitate objects against the earth's gravity. Since diamagnetic materials repel the external magnetic field and tend to move away from the magnetic lines of force, one can make use of strong magnets for levitation. Best objects are superconductors which are ideal diamagnetic, especially at low temperatures.

(commons.wikimedia.org/wiki/Category:Videow_of_sperconducting_levitaion – Insert levitation of a magnet on a superconductor.ogv)

Paramagnetism

This type of magnetism normally occurs in atoms/molecule having odd number of electrons where orbital shells have unpaired electrons. This is so because, as from Pauli's Exclusion principle, two electrons in same energy shell have opposite spins. Therefore, if we have even number of electrons, their net spin will be zero and hence no inherent magnetic moment. However, in case of atoms/molecules with odd number of electrons, there exists a net spin moment. In the absence of external magnetic field, these magnetic moments are randomly oriented and we do not experience any magnetism.

Effect of external magnetic field

1. These materials are slightly attracted by the external magnetic field and the magnetic dipoles get aligned in the direction parallel to that of the external magnetic field. As shown in figure 17, the induced dipoles of the material are aligned in direction of external magnetic field **B**.

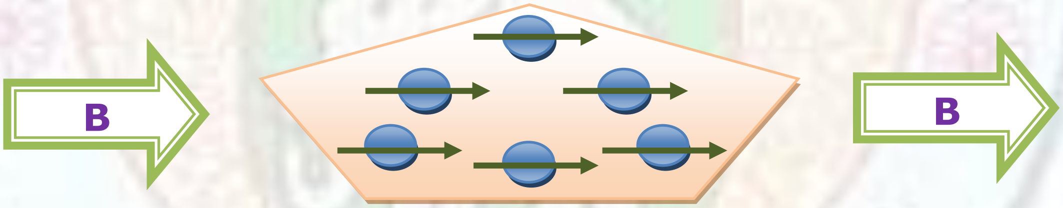


Figure 17

2. If the external applied magnetic field is uniform, then the torque acting on the magnetic dipole tries to align them in the direction of external magnetic field, hence, material orients itself parallel to the field, as shown in figure 18.

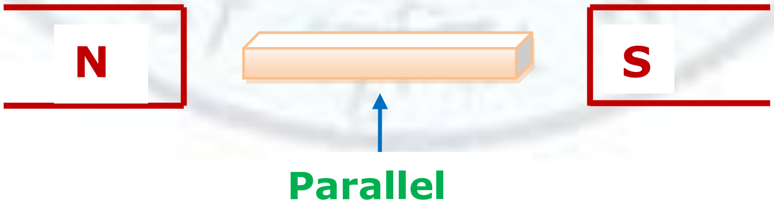


Figure 18

3. If the external magnetic field is non-uniform, then material moves from regions of weaker magnetic field to those with stronger magnetic field. See the orange arrow in figure 19, which is pointing in the direction of increasing magnetic field.

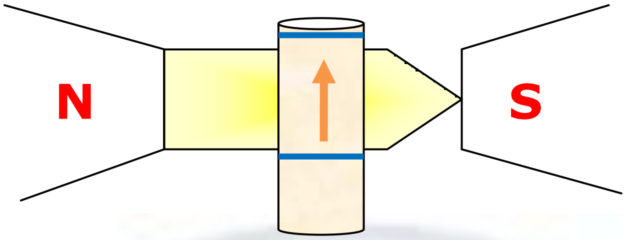


Figure 19

4. When the external magnetic field is removed, then all the magnetic dipoles tend to align in a random manner and hence magnetism is lost, as shown by random dipoles in figure 20.

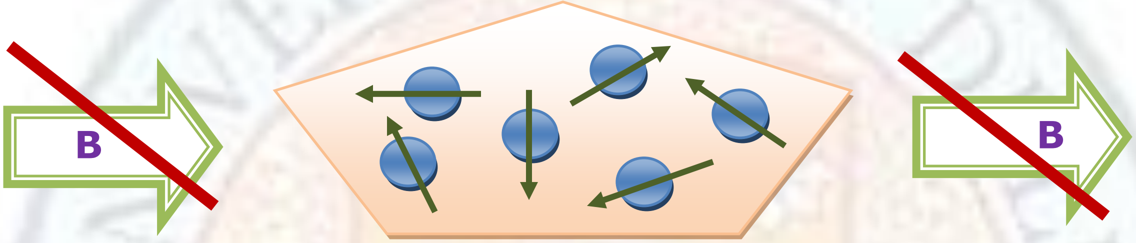


Figure 20

Important characteristics

1. Paramagnetic materials allow magnetic lines of force to permeate through them, as shown in figure 21.

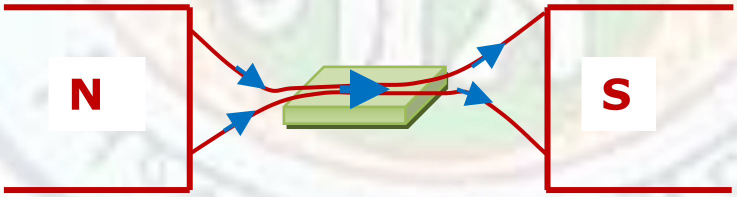


Figure 21

2. Permeability of paramagnetic material ($\mu_{paramagnetic}$) is greater than that of free space (μ_o). The relative permeability is greater than 1 and lines of force pass through the material easily. The variation of magnetic flux density **B** w.r.t applied magnetic field **H** is given in figure 22. The slope of the graph gives permeability of the material.

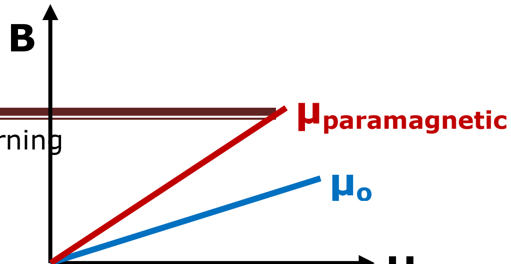


Figure 22

3. The paramagnetic materials are relatively easier to magnetize and hence they have a small positive susceptibility (χ). However, even a small amount of thermal energy is capable of de-aligning the magnetic dipoles. Magnetization (and susceptibility) decreases as the temperature is increased. Hence, paramagnetism is generally stronger at lower temperatures. The variation of magnetization vector **M** w.r.t. applied magnetic field **H** is shown in figure 23(a). The slope of the graph gives susceptibility. The temperature dependence of susceptibility is shown in figure 23(b).

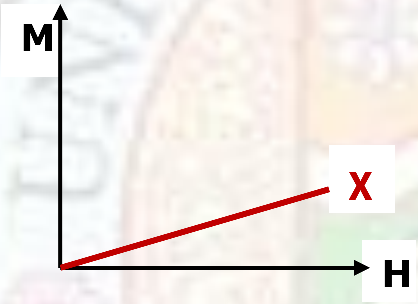


Figure 23(a)

Figure 23(b)

4. Example: magnesium, molybdenum, lithium, tantalum

Did You Know?

1. Since paramagnetic materials have positive susceptibility, and diamagnetic materials have negative susceptibility, therefore, if we make an alloy of paramagnetic and diamagnetic material, then at a certain temperature, the net susceptibility of the alloy will be zero. Such an alloy is very useful to make materials/instruments which are used for sensitive magnetic measurements.

Permeability and Susceptibility

As seen in the previous section, the magnetic field **H**, magnetic flux density **B** and magnetization vector M are related by the relation,

$$H = \frac{1}{\mu_o}\boldsymbol{B} - \boldsymbol{M}$$

$$\Rightarrow \quad \mathbf{B} = \mu_o\,(\mathbf{H} + \mathbf{M})$$

We also know that any object gets magnetized due to application of a magnetic field. The magnitude by which the object gets magnetized is referred to as the susceptibility (χ) of the material and is given by,

$$\mathbf{M} = \chi\,\mathbf{H}$$

$$\text{Hence, } \mathbf{B} = \mu_o\,(\mathbf{H} + \chi\,\mathbf{H})$$

$$\Rightarrow\ \mathbf{B} = \mu_o(1 + \chi)\,\mathbf{H}$$
$$\Rightarrow\ \mathbf{B} = \mu_o\,\mu_r\,\mathbf{H}$$
$$\Rightarrow\ \mathbf{B} = \mu\mathbf{H}$$

Here, μ_r is the permeability of the medium relative to free space. It gives a measure of how much magnetic field is able to permeate through the medium. Hence, μ gives the permeability of the medium and hence gives information about the magnetic flux density of the medium. Figure 24 gives the variation of magnetic flux density **B** w.r.t. applied magnetic field **H** for para- and dia-magnetic materials.

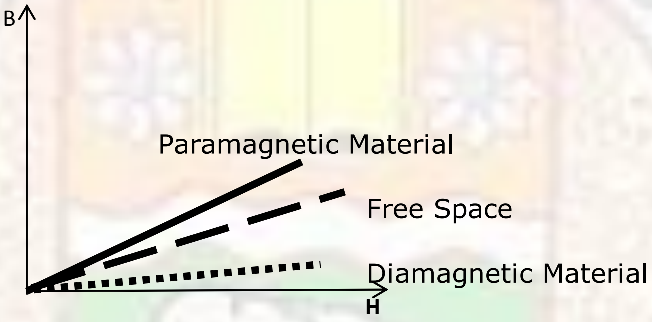


Figure 24

As seen from the B-H plot above, the slope of each line gives the permeability of the material. Clearly, paramagnetic materials have larger permeability than free space. Diamagnetic materials have very small permeability.

Hence, when a magnetic field (**H**) is applied to an object, it gets magnetized by an amount χ**H** (=**M**) and then allows/disallows magnetic lines of force (or magnetic flux density **B**) to pass through them. As discussed before, the magnetic lines of force do not pass through a diamagnetic material, but can easily pass through paramagnetic substance, as shown by a graph in figure 25.

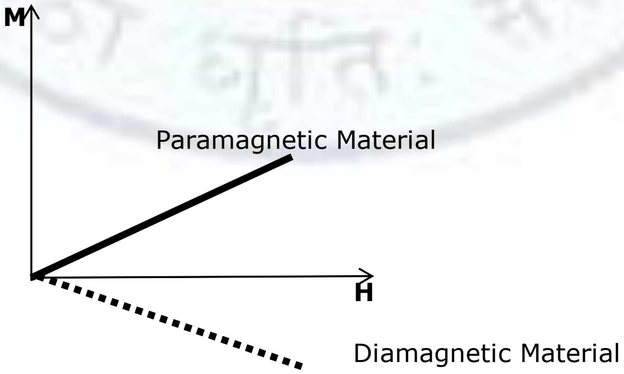


Figure 25

The slope of **M**-**H** curve gives the susceptibility of the between. Paramagnetic materials have a positive susceptibility. Diamagnetic materials do not allow magnetic field to pass through them and hence have a negative susceptibility.

It should also be noted that if the temperature of the substance is increased, its constituent magnetic dipoles become disorganized. Hence the substance becomes less sensitive to the applied magnetic field. In other words, above a critical temperature, the material starts showing non-magnetic behavior. This temperature is called as **Curie's temperature**. Since diamagnetic material has negative susceptibility, therefore, it remains constant with increasing temperature. But susceptibility of a paramagnetic material varies inversely with temperature, as shown in χ vs T plot in figure 26.

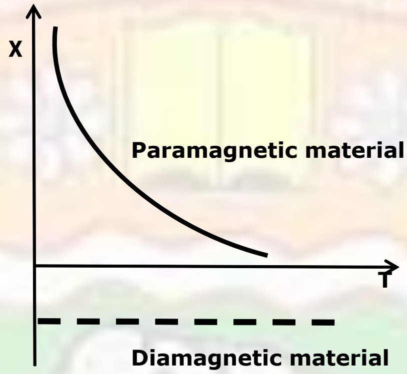


Figure 26

Summary

In this lesson, we have studied the following main points.

1. The inherent magnetic moment of any atom primarily depends on two things. First is the spin motion of electron about its axis of rotation. Second is the orbital motion of electron around the positively charged nucleus.

2. We have studied ways to magnetize a material and have studied the effect of external magnetic field on the material. We have also studied the ways to de-magnetize a material.

2. Based on the above two effects (orbital and spin motion of electrons), a material (in the linear range), either behaves as diamagnetic material or as paramagnetic material.

3. Diamagnetism is a weal effect and is majorly caused due to orbital motion of electrons. We have studied the properties and characteristics of diamagnetic materials.

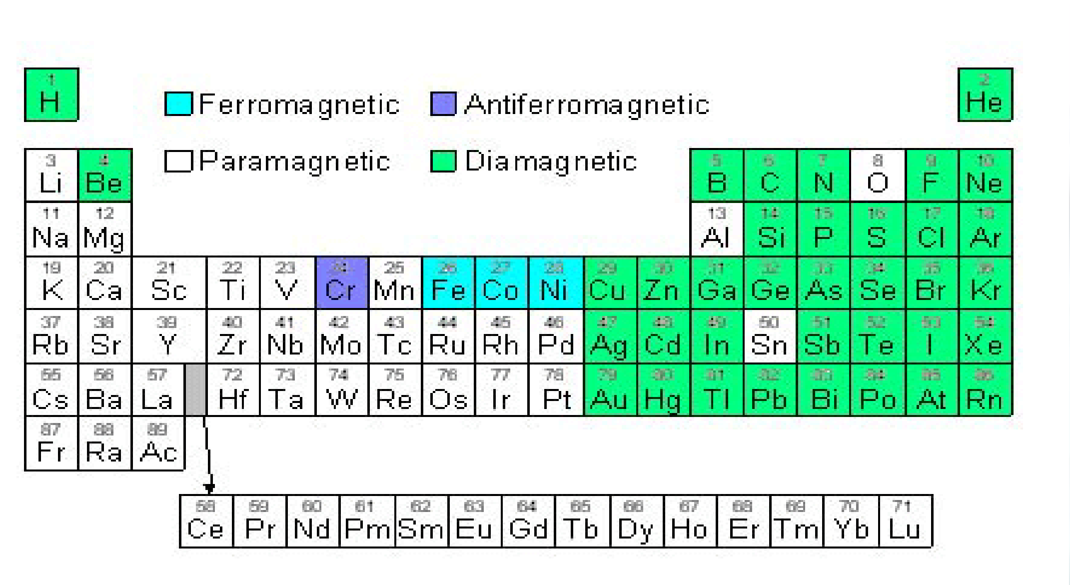
4. Paramagnetism is a relatively stronger effect and is caused due to spin motion of electrons in atoms with odd number of electrons.

5. We have studied the existence of a critical temperature (Curie's temperature) above which the paramagnetic materials loses its magnetism due to thermal motion of the constituent dipoles.

5. We have studied the concept of permeability and susceptibility of a medium.

Did You Know?

1. The periodic table shown below shows the distribution of various elements in reference to their magnetic properties. The various elements in the table have been categorized as diamagnetic, paramagnetic, ferromagnetic and anti ferromagnetic.



2. Common uses of magnets

- ATM / credit/ debit cards
- Speakers and microphones
- Cathode ray tube of a television set
- Recording tapes (CDs, cassettes)

Definitions

Intensity of Magnetization (I): It is the extent to which a substance can be magnetize by applying an external magnetic field. It is the ratio of net magnetic moment within a substance to its total volume.

Intensity of magnetizing field (H): It is the strength of external magnetic field required to induce a net magnetic moment within a substance. It is measure in Ampere/meter or Joule/Tesla-meter^3.

4.1: Magnetic parameters in matter, magnetization, magnetic field, susceptibility, permeability, relation between B, H, M

Magnetic induction (B): It is also called as magnetic flux density. It gives the total number of magnetic lines of force crossing a unit perpendicular area within a substance.

Susceptibility (χ): It is a measure of how easily can materials gets magnetized.

Units and values

Bound surface current density K_b – ampere/meter

Bound volume current density J_b – ampere/meter^2

Magnetization M – ampere/meter

Magnetic induction in material B – tesla

External magnetic field strength H – ampere/meter

Permeability of free space $\mu_o = 4\pi \times 10^{-7}$ H/m = 1.257×10^{-6} H/m

Multiple Choice Questions

1. The type of magnetism which is always present in all the materials is,

   a. Diamagnetism

   b. Paramagnetism

   c. ferromagnetism

   d. ferrimagnetism

   Ans: a

2. We know that $\mathbf{B} = \mu_o \mathbf{H}$, then from Ampere's law,

   a. $\nabla x\, \mathbf{H}$ = bound current density

   b. $\nabla x\, \mathbf{B} = \mu_o$ (bound current density)

   c. $\nabla x\, \mathbf{H}$ = free current density

   d. $\nabla x\, \mathbf{B} = \mu_o$ (free current density)

   Ans: c

3. Identify the equation which holds true for both isotropic and anisotropic materials.

   a. $\mathbf{M} = \chi_m \mathbf{H}$

   b. $\mathbf{B} = \mu_o\mu_r \mathbf{M}$

   c. $\mathbf{B} = \mu_o\mu_r \mathbf{H}$

   d. $\mathbf{B} = \mu_o (\mathbf{H}+\mathbf{M})$

Ans: d

4. Amongst the following, the correct pair of analogous terms in electric field and magnetic fields is,

a. flux density $\mathbf{B_m}$, field intensity $\mathbf{E_e}$

b. field intensity $\mathbf{H_m}$, flux density $\mathbf{D_e}$

c. Magnetization $\mathbf{M_m}$, Polarization $\mathbf{P_e}$

d. Permittivity ε, permeability μ

Ans: c

5. Amongst the following pairs, which one has the same unit?

a. **H**, **M**

b. **H**, **B**

c. **M**, **B**

d. χ_m, μ_o

Ans: a

6. Amongst the following pair of values of susceptibility and relative permeability, the one that is (respectively) true for superconductors is,

a. 0, 0

b. 0, 1

c. -1, 0

d. -1, 1

Ans: c

Fill in the blanks

1. If the magnetization vector is constant everywhere in a magnetized specimen, then _____ will be zero and _____ will be non-zero.

Ans: volume current density, surface current density.

2. _____ vector is a link between microscopic and macroscopic properties of magnetic materials.

Ans: Magnetization

3. A medium having zero susceptibility is _____. (vacuum, superconductor, iron)

Ans: vacuum

4. It is true that in the absence of any external source of magnetic field, the net _____ magnetic field associated with atoms is zero, while _____ magnetic field do exists.

Ans: macroscopic, microscopic

True/False

1. For diamagnetic materials, **M** is not a single values function of **H**.

Ans: It is a false statement. **M** varies linearly with **H** for a diamagnetic material.

2. For paramagnetic materials, magnetization vector varies linearly with magnetic field H.

Ans: It is a true statement.

Short answer question

1. When a magnetic field is applied to an orbiting electron, what will be the magnitude of net force acting on the electron? How will the speed of electron change?

See text

2. What is the susceptibility of free space? Justify.

Ans: zero

3. What is the change in angular velocity of an orbiting electron due to application of a magnetic field **B**?

Ans: Change in angular velocity is $\Delta\omega = (e B)/(2m_e)$

4. Can we measure the bound currents with ammeter?

Ans: No

References

1. Books:

- Principles of Electromagnetics by Matthew N. O. Sadiku, Oxford University Press
- Introduction to Electrodynamics by David J. Griffiths, Pearson Education
- Electricity and Magnetism by D. L. Sehgal, K. L. Chopra, N. K. Sehgal, Pub: Sultan Chand and sons
- Electricity and magnetism by E. M. Purcell, Berkeley Physics Course, Pub: Mc Graw Hill Science

2. Internet:

- Wikipedia
- Commons.wikimedia.org/wiki/Category:Magnetism_diagrams
- www.tutorvista.com/content/physics/physics-iv/magetism-matter/magnetic-properties.php